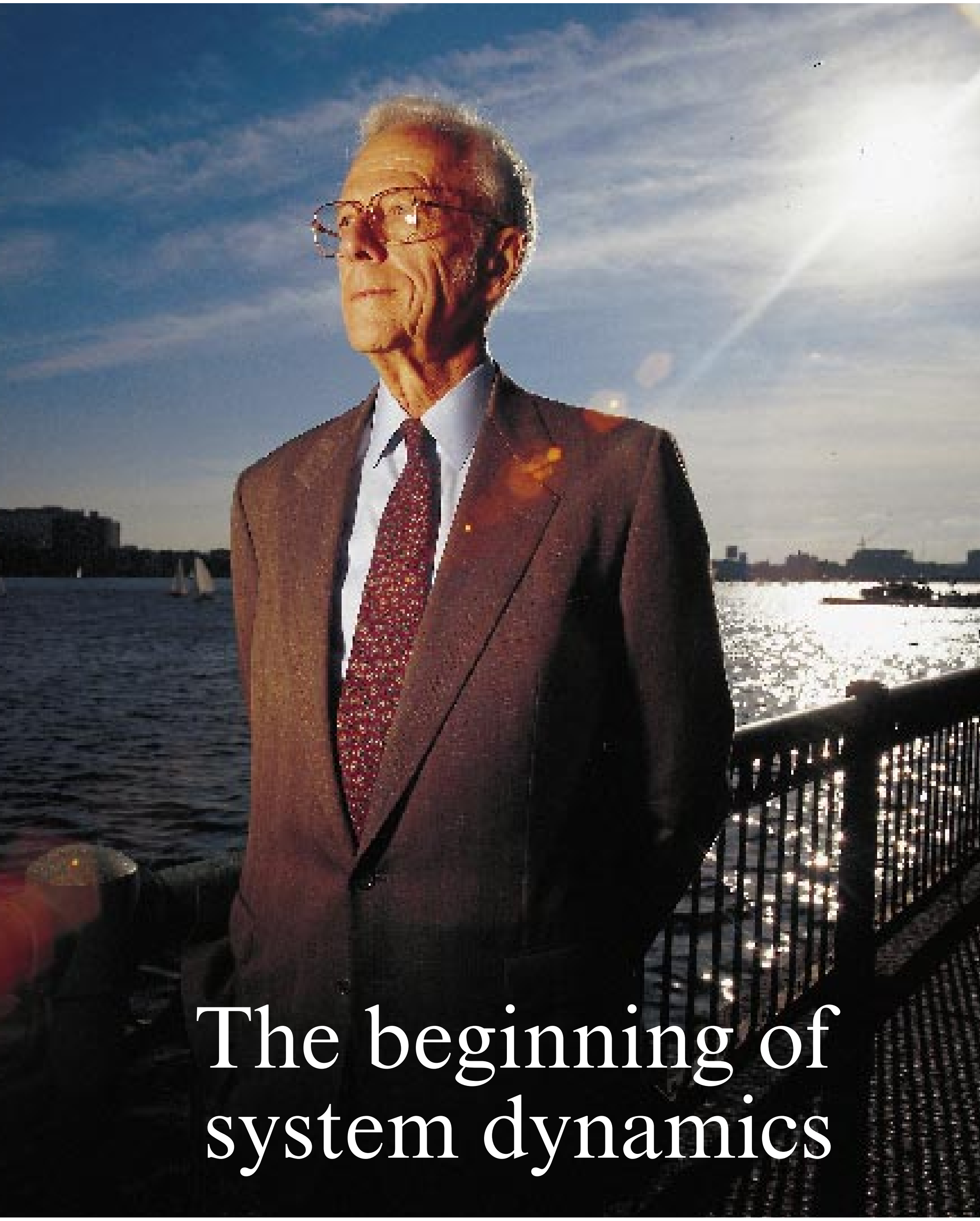
Jay W. Forrester

In the last few years, ideas from a field of engineering instrumental to advances in radar, aircraft simulators, and defense systems have increasingly been applied to management problems. Both managers and consultants have used system dynamics and its principles of feedback and secondary effects to think through how a strategy might or might not work, depending on how competitors react, how organizational changes are received, and what kinds of consequences – intended and unintended – emerge. Many believe that system dynamics has helped them become skilled at inventing the future, either by sketching out causal loops on the back of an envelope, or by assembling equations of cause and effect in a computer model. Both approaches work.

Adapted from a speech given in 1989 by the inventor of system dynamics, Jay Forrester, the following article is both a short history and a helpful primer. Forrester describes how the ideas he used to uncover the real causes of cyclicality in industry could be adopted to explain why low-cost housing has failed to renew inner-city neighborhoods. At the end of the article, a postscript sums up developments that have taken place in system dynamics in the past six years.

Many managers who went to business school fifty or even ten years ago suspected that much of what was being taught about strategy and organization was essentially static in its perspective: the world stood still while we analyzed and fixed it. It is hardly surprising that these managers, having had their suspicions confirmed by their experience in complex, dynamic markets, are now quick to see the relevance of the ideas of Jay Forrester and his colleagues.

Jay Forrester is the founder of system dynamics, Germeshausen Professor, Emeritus at the Sloan School of Management, and the author of a number of books including *Industrial Dynamics, Urban Dynamics,* and *World Dynamics.* This article is adapted from a talk he gave at an international meeting of the System Dynamics Society.



The beginning of system dynamics

BRIAN SMALE

TWO THREADS RUN THROUGH THE STORY of how I came to develop the field of system dynamics. First, everything I have ever done has converged on system dynamics. Second, at many critical moments, when opportunity knocked, I was willing to walk through the open door to what was on the other side.

Early days

I grew up on a cattle ranch in Nebraska in the middle of the United States. A ranch is a crossroads of economic forces: supply and demand, changing prices and costs, the pressures of agriculture. In such a setting, life must be practical; one works to get results. While I was at high school, I built a wind-driven electric plant that provided our first electricity.

When I finished school, I had a scholarship to go to agricultural college, but just before I was due to enroll, I decided it wasn't for me. Instead, I went to the engineering college at the University of Nebraska. Electrical engineering, as it turned out, was about the only academic field with a solid core of theoretical dynamics. And so the road to the present began.

Research and application

After my degree, I became a research assistant at Massachusetts Institute of Technology, where I was commandeered by Gordon S. Brown, a pioneer in feedback control systems. During World War II, we worked on developing servomechanisms for the control of radar antennae and gun mounts. Again, this was research toward an extremely practical end; it ran from mathematical theory right through to the operating field itself.

At one stage, we had built an experimental radar control for an aircraft carrier, to direct fighter planes against enemy targets. It was meant to be redesigned for production a year or so later. The captain of the carrier *Lexington* came to MIT and saw the experimental unit, and said, "I want that, I mean that very one – we can't afford to wait for the production models." He got it.

Life must be practical. At high school, I built a wind-driven electric plant that provided our first electricity

About nine months later, the experimental control stopped working, and I volunteered to go to Pearl Harbor to find out why. I discovered the problem, but didn't have time to fix it before the ship left port, so when the executive officer asked if I would like to go along and finish my job, I said yes. I had no idea what I was letting myself in for. We were off shore during the invasion of Tarawa, and then took a turn through the Marshall Islands, which were occupied all around us by Japanese fighter-plane bases.

LIFELINE: JAY W. FORRESTER

1918
Born in Nebraska

1935–39
Studied electrical engineering at the University of Nebraska

1939
Joined MIT as a research assistant; worked with Gordon S. Brown in developing servomechanisms for controlling radar antennae and gun mounts

1945
Received MSc from MIT

1946
Became Director of the MIT Digital Laboratory

1946–56
Worked on an aircraft flight simulator, which led to the design of the Whirlwind digital computer and the SAGE air defense system

1952–56
Head of the Digital Computer Division of MIT's Lincoln Laboratory

1956
Became Professor of Management at the Sloan School; founded system dynamics

1957
Joined the board of the Digital Equipment Corporation

1961
Published *Industrial Dynamics,* which developed the basic concepts of system dynamics

1968
Published *Principles of Systems*

1969
Published *Urban Dynamics,* which considered how system dynamics could be used to understand America's urban crisis

1971
Published *World Dynamics,* which analyzed the role of systems in the global economy

1972
Received Medal of Honor, Institute of Electrical and Electronics Engineers

1975
Published *Collected Papers*

1979
Inducted into the National Inventors' Hall of Fame

1986
Thomas J. Watson, Jr endowed the Jay W. Forrester Chair of Computer Studies at MIT

1989
Received National Medal of Technology

The Japanese didn't like having a US Navy taskforce wrecking their airports, so they kept trying to sink our ships. After dark, they dropped flares along one side of the taskforce and came in with torpedos from the other. Finally, they succeeded in hitting the *Lexington,* cutting off one of the four propellers and setting the rudder in a hard turn. Again, this gave me a very practical idea of how research and theory are related to field application.

At the end of World War II, my mentor Gordon Brown showed me a list of projects he thought might interest me. From the list, I picked the building of an aircraft flight simulator. This was to be rather like a pilot trainer, but so precise that it could take wind tunnel data for a model airplane and predict the behavior of the new plane even before it was built.

The aircraft simulator was planned as an analog computer. It took us only about a year to decide that an analog machine of that complexity could do no more than solve its own internal idiosyncrasies. Through a long sequence of changes, we came to design the Whirlwind digital computer for experimental development of military combat information systems. This eventually became the SAGE (semi-automatic ground environment) air defense system for North America.

The SAGE system was another practical job where theory and ideas were only as good as the working results. It had 35 control centers, each 160 feet square, four stories high, and with 80,000 vacuum tubes. Installed in the late 1950s, these centers were in service for about 25 years. Records show they were operational 99.8 percent of the time. Even today, such reliability is hard to match.

Why management?

People often ask why I left engineering to go into management. There were several reasons. By 1956, I felt the pioneering days of digital computers were over. This might seem surprising after the major technical advances of the past few decades. But in fact, computers improved more dramatically in terms of speed, reliability, and storage capacity between 1946 and 1956 than in any decade since.

It took a year to decide that a machine of that complexity could do no more than solve its own internal idiosyncrasies

Another reason was that I was already in management. We had been running a several billion dollar operation in which we had complete control of everything: writing contracts, designing computers, deciding what went into production, and managing a vast enterprise that involved the Air Defense Command, the Air Material Command, the Air Research and Development Command, Western Electric, AT&T, and IBM. So going into management was not really a change.

The turning point came when James Killian, then president of MIT, told me about the new management school that was being set up, and suggested that I might be interested. The Sloan School of Management was founded in 1952 with a grant of $10 million from Alfred Sloan, the man who built the modern General Motors Corporation. The money was given with the expectation that a management school in a technical environment like MIT's would probably develop differently from one in a liberal arts setting.

By the time I joined the Sloan School in 1956, I had 15 years' experience in the science and engineering side of MIT, and working out what an engineering background could mean to management seemed like an interesting challenge. I had a year free of other duties to decide why I was at the school.

It had been assumed that applying technology to management meant either pushing forward the field of operations research, or exploring the use of computers in the handling of management information. Neither of these was what I was looking for. Operations research was interesting, and undoubtedly useful, but it did not tackle issues that made the difference between corporate success and failure; it lacked the practical importance that I have always worked toward. As for computers, manufacturers, banks, and insurance companies were already using them, and it seemed unlikely that a few of us in a management school would have much impact, as the momentum was already so great.

The beginning of system dynamics

Chance intervened again when I found myself talking to people from General Electric. They were puzzled as to why their household appliance plants sometimes worked three or four shifts and then, a few years later, had to lay off half their staff. It was easy to say that business cycles caused fluctuating demand, but not entirely convincing.

After finding out how the corporation made hiring and inventory decisions, I started to do some simulation, using a pencil and a page in a notebook. At the top, I put columns for inventories, employees, and orders. Given these conditions and the policies being pursued, one could predict how many people would be hired the following week. This produced a new set of conditions for inventories, employment, and production.

It became clear that here was the potential for an oscillatory or unstable system that was entirely internally determined. Even if incoming orders remained constant, employment instability could still arise as a consequence of common decision-making policies. This first pencil and paper inventory control system was the beginning of system dynamics.

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It also marked the origins of what are now the DYNAMO compilers. Richard Bennett, an expert computer programmer, was working with me when I wrote an article for the *Harvard Business Review* in 1958. I needed computer simulations for the article, and suggested he code up the equations so that we could run them on our computer. However, being an independent type, Dick said he would not code the program, but would instead produce a compiler that would automatically generate the computer code.

The result was the SIMPLE compiler – Simulation of Industrial Management Problems with Lots of Equations. Bennett's insistence on creating a compiler was another turning point; it accelerated the modeling that rapidly expanded system dynamics. The early compiler was extended by Alexander Pugh III into the highly influential DYNAMO series.

At about this time, I was asked to join the board of the Digital Equipment Corporation, because several of its founders had worked for me in the Whirlwind computer days. I did not understand the nature of high-technology growth companies as well as I wished to, and undertook to model such companies to guide my own position on the board. This modeling afforded a number of insights about why high-technology companies often grow to a certain size and then stagnate or fail. It moved system dynamics out of physical variables like inventory into much more subtle considerations: the top management influence structure, leadership qualities, the characters of the founders, how goals are set, the interactions between capacity, price, quality, and delivery delay, and how an organization's traditions determine its decision making and its future.

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Wider applications

A series of incidents in 1968 shifted the focus of system dynamics from corporate modeling to broader social systems. John F. Collins, mayor of Boston for eight years, decided not to run for reelection, and accepted a one-year appointment as Visiting Professor of Urban Affairs at MIT. He ended up in the office next to mine. In talking with him about the time he spent coping with Boston's urban problems, I experienced the same feeling that I had come to recognize in conversations with business executives. The story sounded persuasive, but it left an uneasy sense that something was wrong or incomplete.

I suggested to Collins that we might combine our efforts, taking his experience in Boston and my background in modeling and looking for interesting insights about cities. He immediately asked how to go about it. I told him we would need advisers who knew a great deal about cities from personal experience – people who had struggled with cities, who had worked in them, who knew what really happens. But we would not be able to predict what would come of the effort, or how long it would take. We would have to gather a group half a day a week, probably for months, to seek an understanding of the structure and processes of cities that might explain stagnation and unemployment.

Collins listened and said, "They'll be here on Wednesday afternoon." Such was his position in Boston at that time that he could call up almost anybody in politics or business, ask for their Wednesday afternoons for a year, and get them. He delivered the people, and it was out of these discussions that my book *Urban Dynamics* developed.

Strong reactions

Urban Dynamics was the first of my modeling work to produce strong emotional reactions. It suggested that all of the major urban policies being pursued by the United States lay somewhere between neutral and highly detrimental in their impact, whether from the viewpoint of the city as an institution or from the perspective of unemployed, low-income residents. More, it argued that the most damaging policy of all was to build low-cost housing. At that time, this policy was thought essential to reviving the inner cities.

The conclusions of our work were not easily accepted. It took people several hours to come to an understanding of what urban dynamics was about. City officials and members of local communities would become more and more negative and emotional until they could see and accept the way in which low-cost housing was a double-edged sword for making urban conditions worse. Such housing used up space where jobs could have been created, while drawing in people who needed jobs. Building low-cost housing was a powerful process for *producing* poverty, not alleviating it.

> *Urban Dynamics* argued that low-cost housing was a double-edged sword for making urban conditions worse

Soon after *Urban Dynamics* came out, I was asked to lead two sessions on a four-week management program for senior urban executives from large cities. I have never had a lecture on any subject, anywhere, go as badly as the first of these sessions. In the group was a member of the New York city government who came from the black community in Harlem. Intelligent, articulate, he didn't buy a thing I was saying, and he carried the group with him.

At one point, he said, "This is just another way to trample on the rights of the poor people, and it's immoral." At another, "You're not dealing with the black versus white problem, and if you're not dealing with the black versus white problem, you're not dealing with the urban problem." When I said decay and poverty in inner cities were exacerbated by too much low-cost housing, not too little, he looked at me and remarked, "I come from Harlem, and there's certainly not too much housing in Harlem." That is a sample of the first session; the mood of the group had become very hostile.

An hour into the second session, the New Yorker's comments began to change. Instead of tearing down what I was saying, he asked questions to elicit information. An hour later, he said, "We can't leave the subject here.

We must have another session." I ignored the request at first, and he repeated it twenty minutes later. I agreed to meet the group again if he could find a time and place in the program.

He went to the administration and scheduled another session, and later made an appointment to see me, when he asked if I would talk to a group that he would invite in New York – his colleagues on his turf. As relaxed as could be, he sat in my office and said, "You know, it's not a race problem in New York at all, it's an economic problem." He got out a report and gave it to me. It documented the amount of empty housing in every borough of New York, and the rate at which it was being abandoned.

My point had been that "too much" housing meant that there was too much for the economy of the area to support. He had all the proof in his briefcase. He simply had not realized what his knowledge meant until it was all put together in a new way.

My point was that "too much" housing meant that there was too much for the economy of the area to support

Two years later, a journalist asked me what people thought in the aftermath of *Urban Dynamics*. I suggested he talk, among others, to the man in New York, with whom I had had no contact in the intervening period. Later, the journalist called me up to report that he had been told, "They don't just have *a* solution to the urban problem up there in Boston, they have *the only* solution." The lesson about urban behavior had stayed clear and alive for two years, even back in the New Yorker's home environment. The five hours of exposure to urban dynamics had left a lasting impression. But we have not yet cracked the challenge of how to bring enough people across the barrier separating their usual simple, static viewpoint from a more comprehensive understanding of dynamic complexity.

Modeling the world

Urban Dynamics was the key that led to the *World Dynamics* and *Limits to Growth* projects. At a meeting on urban difficulties in Italy, I met Aurelio Peccei, founder of the Club of Rome. Later, in June 1970, I was invited to a Club meeting in Berne, Switzerland. This became another turning point in my career in system dynamics.

The world problems discussed at the Berne meeting became the basis for the model that appears in *World Dynamics*, which was used in a two-week meeting with the Club of Rome's executive committee at MIT in July 1970. The committee decided to support research at MIT to take the material further. One of its members, Eduard Pestel, arranged funding for the research, which eventually produced *The Limits to Growth*.

The public responses to system dynamics have always surprised me. I have usually been wrong in anticipating the impact my books will make. *World Dynamics* seemed to have everything necessary to guarantee no public notice: 40 pages of equations in the middle of the book; key messages in the form of computer output graphs; and a publisher that had only published one book before. I thought I was writing for maybe 200 people who would like to try an interesting model on their computers. But I was wrong.

World Dynamics came out in the first week of June, 1971. Three weeks later, it was reviewed on the front page of the British *Observer*. It was discussed in the *Singapore Times*, the *Christian Science Monitor*, *Fortune*, the *Wall Street Journal*, and *Playboy*. (This last publication was a disappointment as a vehicle for system dynamics. Out of eight million copies in circulation, the only response I ever received was from a man at the National Council of Churches.) The book ran through the editorial columns of mid-America's newspapers, was the subject of prime-time European television documentaries, and got debated in the environmental press, the zero population growth press, and the underground student press.

Public responses have always surprised me. I have usually been wrong in anticipating the impact my books will make

The Limits to Growth was published nine months later. After the media attention *World Dynamics* had attracted, I thought that the second book might be an anticlimax; it had essentially the same message, although more work had been done and it was written in a more popular style. I was wrong again. Public attention went up by about a factor of ten.

The dynamics of economic systems

Urban Dynamics led not only to these two world environment books, but also to work on the System Dynamics National Model, an effort to model the behavior of the US economy and the impact of public policy. After I gave a talk at a joint NATO/US conference on cities, William Dietel, the recently retired president of the Rockefeller Brothers Fund, came up from the audience. From that meeting came initial funding for our work in applying system dynamics to the behavior of economic systems.

The National Model identified for the first time the feedback loops causing the economic long wave (or Kondratieff cycle) with peaks followed by major depressions some 45 to 65 years apart. The short-term business cycle (three to ten years between peaks) involves an overbuilding and underbuilding of consumer durables. In a similar way, the economic long wave arises mostly from the overbuilding of capital plant and the excessive debts associated with it, followed by the collapse of production of physical capital and the repayment of debt.

One often sees assertions in the social science literature that the act of studying an organization will alert people to questions about their actions, and that the process of being studied will cause changes in behavior. I do not believe this is true. It is much harder to change decision-making procedures than we realized when system dynamics started. Old mental models and decision habits are deeply ingrained; they do not change just because of a logical argument.

Early system dynamics analyses were in the "consultant" mode: the practitioner would study a corporation, go away and build a model, and come back with recommendations. In most cases, these suggestions would be accepted as sound, but they would not alter behavior. Under the pressure of day-to-day operations, decisions would revert to prior practice.

Recent trends in system dynamics aim to change the mental models that people use to represent the real world. For this to happen, individuals must be sufficiently involved in the modeling process to internalize lessons about dynamic feedback behavior. This exposure to dynamic thinking should start at an early age, before contrary patterns of thought have been irrevocably established. Apparently, students as young as ten can benefit from exposure to cause and effect thinking and computer modeling.

System dynamics is being introduced into junior and senior high schools through the efforts of a number of teachers, my old mentor Gordon Brown among them. To recap, it was he who originally got me involved with feedback systems in the MIT Servomechanisms Laboratory in the early 1940s. He later became head of the electrical engineering department, and then dean of engineering. In the meantime, I went on to develop computers and the field of system dynamics on the basis of that background in feedback systems.

It is much harder to change decision-making procedures than we realized when system dynamics started

Recently, Gordon has completed the circle by picking up system dynamics and taking it to a junior high school in the town where he spends the winter. He started by lending STELLA software for a weekend to Frank Draper, a biology teacher. Draper came back on Monday to say, "This is what I have always been looking for; I just did not know what it could be." At first, he expected to use computer simulation in one or two classes a term; then he found that systems thinking and simulation were becoming part of every class.

After a while, he became concerned that he would not be able to cover the biology syllabus if he spent so much time on system dynamics. But two-thirds of the way through the term, he discovered he had completed all the necessary biology content. In fact, learning was proceeding at a much more rapid pace thanks to the integrative approach and greater student involvement made possible by the systems viewpoint, along with the learner-directed organization that was introduced at the same time. Draper concluded, "There *is* a free lunch."

In management education, we should look forward to a major breakthrough in scope and effectiveness when we move beyond the case study method and fully adopt system dynamics. Pioneered by the Harvard Business School, case studies made their first appearance around 1910, and are still widely used around the world. A case study, like a system dynamics analysis, starts by gathering and organizing information from an actual managerial setting. But the case study leaves this information in a descriptive form that cannot reliably cope with the dynamic complexity that is involved.

Whether in school or management education, the focus will be on "generic structures"

System dynamics, on the other hand, can organize the descriptive information, retain the richness of the real processes, build on the experiential knowledge of managers, and reveal the dynamic behaviors that follow from different policy choices. I believe that system dynamics will become the frontier of new developments in management education over the next twenty years.

Whether in school or management education, the focus will be on "generic structures" – a small number of fairly simple structures that can be found over and over again in different businesses, professions, and real-life settings. One of Frank Draper's junior high school students was working with bacteria, and looked up to observe, "This is the world population problem, isn't it?" Such transfers of insights from one context to another will help to break down the boundaries between disciplines. Learning in one field will become applicable to others.

There is now the promise of reversing the trend of the last century: the movement away from "Renaissance man," the gifted all-rounder, toward fragmented specialization. We can work toward an integrated educational process that is more efficient, more appropriate to a world of increasing complexity, and more compatible with a unity in life.

Postscript

In the six years since I gave this talk, system dynamics has continued its exponential growth, with activity doubling about every three years. It now reaches into areas far beyond our original expectations. Business applications are expanding rapidly, with in-house corporate groups and a growing number of qualified consultants bringing expertise to bear. Indeed, corporate involvement with system dynamics goes much further than we can readily observe, because the best work is surrounded by a high degree of confidentiality. If more of these business applications can be made public, it will advance the field and encourage business schools to expand systems education. Advances in system dynamics software are helping applications to spread. The original DYNAMO software has been further developed, while STELLA and ithink, both with excellent manuals, have provided a user-friendly way to start in the field. Powersim has recently come on the market as an alternative entry-level package with several advanced features. At the top end, Vensim provides powerful facilities for working with larger models and tracing the causes of dynamic behavior. For the long-term future of system dynamics and our better understanding of social and business systems, the most exciting developments lie in pre-college education. Successful experiments are emerging as system dynamics shows it can become a foundation for nearly all subjects from kindergarten to high school. Several dozen schools are demonstrating that it can provide a unifying basis to connect mathematics, physics, biology, environmental issues, economics, business, social studies, and literature. System dynamics deals with how things change through time. Almost all human concerns relate to how the past led to the present, and how today's actions determine the future. Schools become challenging and exciting places when study relates to the community and to issues that touch on students' lives. Q

There is now the promise of reversing the trend of the last century toward fragmented specialization

SUGGESTED READING

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George P. Richardson, *Feedback Thought in Social Science and Systems Theory,* University of Pennsylvania Press, Philadelphia, Pa., 1991.

of interest...

POSITIVE FEEDBACKS IN THE ECONOMY

"In the real world, if several similar-size firms entered a market at the same time, small fortuitous events – unexpected orders, chance meetings with buyers, managerial whims – would help determine which ones achieved early sales and, over time, which firm dominated. Economic activity is 'quantized' by individual transactions that are too small to observe, and these small 'random' events can accumulate and become magnified by positive feedbacks so as to determine the eventual outcome. These facts suggested that situations dominated by increasing returns should be modeled not as static, deterministic problems, but as dynamic processes based on random events and natural positive feedbacks, or nonlinearities."

W. Brian Arthur
An excerpt from *Scientific American,* February 1990 and reprinted in *The McKinsey Quarterly,* 1994 Number 1

Editor's note: In "The paradox of fast growth tigers" (*The McKinsey Quarterly,* 1995 Number 3), Zafer Achi, Andrew Doman, Olivier Sibony, Jayant Sinha, and Stephan Witt use the fundamental tenets of positive feedback and increasing returns economics, especially the work of W. Brian Arthur of the Santa Fe Institute, to explain the way 41 publicly listed companies managed to increase their revenues and operating income by 20 percent per year by focusing on one major line of business. During this period of sustained fast growth, these companies created over 300,000 jobs and added $110 billion in market value – beating the competition over and over again. Professor Arthur's ideas on increasing returns are brought together in his book, *Increasing Returns and Path Dependence in the Economy,* The University of Michigan Press, Ann Arbor, 1994.